EXPERIMENTAL INVESTIGATION OF MICRODRILLING OPERATION OF PRINTED CIRCUIT BOARD

A thesis submitted in partial fulfillment of the requirement for the degrees of

Bachelor of Technology

In

Mechanical Engineering

By

TAPAS KUMAR MAHATO

ROLL NO.-109ME0381

DEPARTMENT OF MECHANICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

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UNDER THE SUPERVISION

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CERTIFICATE

This is to certify that the thesis entitled " *Experimental investigation of micro drilling operation of printed circuit board.*" submitted by Tapas Kumar Mahato (109ME0381) in fulfillment of the requirement for the award of Bachelor of Technology Degree in Mechanical Engineering at the National Institute of Technology, Rourkela is a genuine work carried out under my supervision.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

DATE-

PLACE-

Prof. K P Maity
Head of department,
Department of Mechanical Engineering
NIT Rourkela, 769008

ACKNOWLEDGEMENT

I wish to express my gratitude and indebtedness to my project supervisor *Prof K. P. Maity*, HOD, Department of Mechanical Engineering, NIT Rourkela, for his helpful hand, inspiring guidance, constructive criticism and moral support.

I would also like to thank *Mr. Kunal Nayek*, employee member of the production Engineering Laboratory and *Mr. Kumar*, CNC operator for assistance and facilitate in completing experiments.

DATE-

PLACE-

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ABSTRACT

In this present age the application of micromachining operations continues to grow. These operations are required to fabricate the products required for sectors like medical science, automobile industries and electronics manufacturing etc. which deals with miniature trends. Micro drilling process is one of the micromachining process which is used to drill micro holes not only in micro products but also in relatively larger work pieces which require ultra-small features which can be accomplished only by micromachining process. Small highly accurate holes are a common requirement across various industries and applications. In this paper, the investigation of micro drilling on copper coated printed circuit board (PCB) has been reported. Taguchi methodology has been used to plan the experiments and by using grey rational grades the optimum process parameters have been calculated. The process parameters considered in this case are spindle speed and feed rate. The torque, thrust force, time of machining and circularity has been measured. An attempt to calculate the influence of these parameters on the response variables has been made in order to plan an economically feasible machining operation. The optimum values for the process parameters have been identified by using signal to noise ratio analysis of grey relational co-efficients.

List of figures

List of tables

INTRODUCTION

Micro drilling process is used to produce small highly accurate holes which is a common requirement across large number of industries and applications. Industries and applications that require huge volumetric production, the drilling time and the finishing of the hole, rivals the cost of the process. So an intensive study of the machining process is required to make the production economical. Drilling refers to a metal removal process which removes a circular cross section from the work piece. The drill bit which is a multipoint cutting tool in most cases is pressed against the material and rotated which cuts of chip from the material and this results in the formation of hole. Drilled holes are characterized by their sharp edge on the entrance side and the presence of burrs on the exit side. Helical feed marks are also present inside the hole. Drilling also affects the mechanical properties of the material. So in order to find out the local circularity error, the use of optical microscope (SEM) is required. The forces acting during the operation is measured using dynamometer. L_9 orthogonal array is used for DOE purpose. The work piece used is copper coated PCB. Drilling operation is performed on a CNC machine by coding an appropriate program. The drill bit used in this case has a diameter of 1 mm. The burr formed during the drilling operation must also be examined and analyzed in order to reduce it in future operation.

CHAPTER 1: DRILLING PROCESS

Drilling is the method of making holes in a work piece with metal cutting tools. Drilling is associated with machining operations such as trepanning, counter boring, reaming and boring. A main rotating movement is common to all these processes combined with a linear feed. There is a clear distinction between short hole and deep hole drilling.The drilling process can in some respects be compared with turning and milling but the demands on chip breaking and the evacuation of chips is critical in drilling. Machining is restricted by the hole dimensions, the greater the hole depth, the more demanding it is to control the process and to remove the chips. Short holes occur frequently on many components and high material removal rate is a growing priority along with quality and reliability.

Solid drilling is the most common drilling method, where the hole is drilled in solid material to a predetermined diameter and in a single operation.

Trepanning is principally used for larger hole diameters since this method is not so power-consuming as solid drilling. The trepanning never machines the whole diameter, only a ring at the periphery. Instead of all the material being removed in the form of chips, a core is left round the center of the hole.

Counter boring is the enlargement of an existing hole with a specifically designed tool. This machines away a substantial amount of material at the periphery of the hole.

Reaming is the finishing of an existing hole. This method involves small working allowances to achieve high surface finish and close tolerances.

The cutting speed, or surface speed (v_c) in for drilling is determined by the periphery speed and can be calculated from the spindle speed (n) which is expressed in number of revolutions per minute. During one revolution, the periphery of the drill will describe a circle with a circumference of $\pi \times D_c$, where D_c is the tool diameter. The cutting speed also varies depending upon which cutting edge across the drill-face is being considered.

A machining challenge for drilling tools is that from the periphery to the center of the drill, the cutting speed declines in value, to be zero at the center. Recommended cutting speeds are for the highest speed at the periphery.

The feed per revolution (f_n) in mm/rev expresses the axial movement of the tool during one revolution and is used to calculate the penetration rate and to express the feed capability of the drill.

The penetration rate or feed speed (v_f) in mm/min is the feed of the tool in relation to the work piece expressed in length per unit time. This is known as the machine feed or table feed. The product of feed per revolution and spindle speed gives the rate at which the drill penetrates the work piece. The hole depth (L) is an important factor in drilling as is the radial cutting depth (a_p) and feed per tooth (f_z) for calculations.

Machining holes

Holes are either made or finish machined. Most work pieces have at least one hole and depending upon the function of the hole, it needs machining to various limitations.

The main factors that characterize

A hole from the machining view point are:

- diameter
- depth
- quality
- material
- conditions
- reliability
- productivity[14],[15]

CHAPTER 2: PRINTED CIRCUIT BOARDS

Printed Circuit Board (PCB) is used to mechanically support and electrically connect electronic components using conductive pathways, tracks original traces etched from copper sheets laminated onto a non-conductive substrate.

Printed circuit boards manufactured now a days can be built using the following four items:-

- Copper-clad laminates.
- Resin impregnated B-stage cloth
- Copper foil.
- Laminates.

Majority of printed circuit boards are made from purchased laminate material with copper applied to both sides. The non-useful copper is removed by various methods leaving only the desired copper traces, this is called subtractive. Holes through a PCB are typically drilled with small-diameter drill bits made of solid coated tungsten carbide. Coated tungsten carbide is used since board materials are very abrasive and drilling must be done at high RPM and high feed to be cost effective. Drill bits should remain sharp so as not to tear the traces. Drilling with HSS tool is simply not feasible since the drill bits will dull quickly and thus tear the copper and ruin the boards. The drilling operation done by automated drilling machines with placement controlled by a drill tape or drill file. These computer-generated files are also known as numerically controlled drill. These holes are often filled with annular rings (hollow rivets) to create vias. Vias allow the electrical and thermal connection of conductors on opposite sides of the PCB. [13]

CHAPTER 3: LITERATURE REVIEW

Micromachining operations play an important role in precision production industries. Out of the various machining processes, micro-drilling is used to produce micro holes in fuel injectors, printed circuit board, aerospace materials etc. So in order to achieve the optimum working conditions various research were conducted by different researchers from across the globe. This report reviews some of the journal published by them regarding optimization processes.

Yogendra Tyagi,Vadansh Chaturvedi and Jyoti Vimal [1] have conducted an experiment on drilling of mild steel, and applied the taguchi methods for determining the optimum parameters condition for the machining process using the taguchi methods and analysis of variance. The work piece used is mild steel (100mm×76mm×12mm) and the tool used is HSS with a point angle of 118° and diameter of 10 mm. Taguchi L_9 orthogonal arrays is used here in order to plan the experiment. The input parameters are feed rate, depth of cut and spindle speed whereas the output responses are surface roughness and metal removal rate (MRR).In case of signal to noise ratio calculation, larger the better characteristics is used for calculation of S/N ratio for metal removal rate and nominal and small the better characteristics is used for the calculation of S/N ratio for surface roughness. After the analysis of the data obtained it is found that MRR is affected mostly by feed. Confirmation experiment was conducted using the data obtained from S/N ratio graphs and it confirmed with the results of taguchi methodology. In case of surface roughness analysis same procedure was followed where the significant parameter was found to be the spindle speed. Here too the confirmation experiment was conducted and this confirms the successful implementation of taguchi methods.

Timur Canel,A. Ugur Kaya,Bekir Celik [3] studied the laser drilling on PVC material in order to increase the quality of the cavity. Taguchi optimization methods was used to obtain the optimum parameters. The material used in the experimental setup is PVC samples with dimensions of 5mm×85mm×4.5mm. Surelite Continuum Laser is used to form the cavities. The input parameters are wavelength, fluence and frequency and the output response are aspect ratio, circularity and heat affected zone. Taguchi L_9 orthogonal array is used to find the signal to noise ratio. Smaller the better characteristics is used for HAZ, larger the better characteristic is used for aspect ratio and nominal the better characteristic is used for circularity. Variance analysis is performed using the calculated S/N ratio to conclude optimum stage. It is found that most effective parameter for aspect ratio is frequency, second is wavelength and last is fluence. For circularity it is found that the most effective parameter is wavelength, fluence and frequency. For HAZ it is found that the most effective parameter is wavelength, second is frequency and last is fluence. The experimental results are compatible with Taguchi method with 93% rate.

Thiren G. Pokar,Prof. V. D. Patel[5] used grey based taguchi method to determine the optimum micro drilling process parameters.

B.Shivapragash,K.Chandrasekaran,C.Parthasarathy,M.Samuel [6] have tried to optimize the drilling process involving metal matrix composites(MMC) in order to minimize the damage done to it during the process by using taguchi and grey rational analysis. The work piece used is Al-$TiBr_2$(MMCs),with dimension of 100mm × 170mm × 15mm.The tool material is HSS with diameter of 0.6 mm. The input parameter are spindle speed, depth of cut and feed rate whereas the output parameter are MRR and surface roughness. For finding out the optimal combination of cutting parameters the results are converted into S/N ratios and higher the better type characteristics is used for MMR, and smaller the better characteristics is used for surface roughness.

Wen Jialing and Wen Pengfei [8] used an orthogonal experimental design in order to find out the optimum process parameters for injection molding of aspheric plastic lens, to reduce volumetric shrinkage and volumetric shrinkage variation. Six input parameters were taken, each with 5 levels(Fill Time/sec, holding pressure/Mpa, holding pressure/times, cooling time/s, melt temperature/°C, mold temperature/°C.$L_{25}(5^6)$ orthogonal array is used to plan the above experiment. The parameters affecting both volumetric shrinkage and volumetric shrinkage variation are identified in order.

CHAPTER 4: EXPERIMENTAL LAYOUT

SETUP

The work piece used in this case is a copper coated printed circuit board. The drill-bit which is applied in this experiment is solid carbide drill-bit which is a type of straight shank twisted drill. The standard diameter of this type of drill-bit is 1mm. The point angle and flute length are 118° and 23 mm respectively. The output parameter of torque and thrust force was measured by the arrangement of 9272A type Kistler Co. prepared quartz 4 component dynamometer and 5070A type multi-channeled charge amplifier. And the local circularity error and time are measured by means of JEOL SEM-6480LV machine and stop watch respectively.

DRILL BIT SPECIFICATIONS

Type - Solid carbide drill

Diameter – 1 mm

Flute length - 23mm

Point angle -118°

WORK PIECE

PCB Copper Coated

AMPLIFIER

Type - 5070A

Company – Kistler

[9]

LATHE DYNAMOMETER

The forces experienced by the work piece material during the cutting process is measured using the lathe dynamometer. The forces experienced by a tool while drilling operation are, the cutting force is represented as Fc (Fz), the feed force as Fs (Fx) and the thrust force as Ft (Fy). The work piece is mounted on the dynamometer and the forces are picked up by the charged amplifier which are displayed on digital display.
[9]

Fig no.1, Tool dynamometer

Type-9272A

Company-Kistler

DYNAMOMETER SPECIFICATIONS

Technical Data

Measuring range	F_x, F_y	kN	–5 … 5 [1)]
	F_z	kN	–5 … 20 [2)]
	M_z	N·m	–200 … 200
Calibrated measuring range			
100 %	F_x, F_y	kN	0 … 5
	F_z	kN	0 … 20
	M_z	N·m	0 … 200
			0 … –200
10 %	F_x, F_y	kN	0 … 0,5
	F_z	kN	0 … 2
	M_z	N·m	0 … 20
			0 … –20
Overload	F_x, F_y	kN	–6/6
	F_z	kN	–6/24
	M_z	N·m	–240/240
Max. bending moment	M_x, M_y	N·m	–400 … 400
Threshold	F_x, F_y	N	<0,01
	F_z	N	<0,02
	M_z	mN·m	<0,2
Sensitivity	F_x, F_y	pC/N	≈–7,8
	F_z	pC/N	≈–3,5
	M_z	pC/N·m	≈–160
Linearity, all ranges		% FSO	≤±1
Hysteresis, all ranges		% FSO	≤1

Crosstalk	$F_x \leftrightarrow F_y$	%	≤±2
	$F_z \rightarrow F_{x,y}$	%	≤±1
	$F_{x,y} \rightarrow F_z$	%	≤±2
	$F_z \rightarrow M_z$	mN·m/N	≤±0,2
	$M_z \rightarrow F_z$	N/N·m	≤±1
	$F_{x,y} \rightarrow M_z$	mN·m/N	≤±0,7
	$M_z \rightarrow F_{x,y}$	N/N·m	≤±0,5
Rigidity	c_x, c_y	kN/µm	≈0,4
	c_z	kN/µm	≈2
	cM_z	N·m/µrad	≈0,7
Natural frequency	f_n (x,y)	kHz	≈3,1
(mounted on rigid base)	f_n (z)	kHz	≈6,3
	f_n (M_z)	kHz	≈4,2

Operating temperature range		°C	0 … 70
Temperature coefficient of sensitivity		%/°C	–0,02
Capacitance	F_x, F_y, F_z	pF	185
	M_z	pF	420
Insulation resistance (20 °C)		Ω	$>10^{13}$
Ground isolated		Ω	$>10^8$
Connector		Fischer flange 9-pole neg.	
Degree of protection EN60529		–	IP67 [3)]
Weight		kg	4,2

CHAPTER 5: PROCEDURE

At first the piezoelectric dynamometer is mounted on the bed of the CNC drilling machine with the help of T-bolts. Then the work piece (PCB) is mounted on top of the dynamometer with the help of bolts and washer. By using proper drilling CNC program the input parameters are varied. The output responses are displayed on the amplifier monitor. Moreover the circularity error and the burr formation is to be examined using a scanning electron microscope (JEOL SEM, at an accelerating voltage of 15KV and magnification of X70).The step feed used in this case is 0.2 mm.

Experimental Design

Design of experiment is the design of any information gathering experiment where variation is present, whether under full control of the experimenter or not. Taguchi methods are statistical method applied to problems in engineering, marketing etc. In this particular case we have used L_9 orthogonal arrays with 2 input parameters at 3 levels each. Hence the total number of experimental runs is 9.

TABLE NO- 1, Input process parameters

Parameter	Code	Level 1	Level 2	Level 3
Feed rate(mm/min)	A	5	10	15
Spindle Speed(RPM)	B	1000	1500	2000

Grey Rational Analysis

- Determination of experimental data tables through Design of Experiments.
- Normalize the response parameters in the domain of < 0, 1 > by using following formula of lower the best

$$N_{ij} = \frac{(X_{ij})_{max} - X_{ij}}{(X_{ij})_{max} - (X_{ij})_{min}}$$

Where $\mathbf{N_{ij}}$= Normalized value after grey relational generation

$\mathbf{(X_{ij})_{max}}$= Maximum value of response parameter

$\mathbf{(X_{ij})_{min}}$= Minimum value of response parameter and

$\mathbf{X_{ij}}$= Value of response in ith column and jth raw of design matrix.

NOTE: Here i value varies from 1 to 4 and j value varies from 1 to 9.

- Grey relational co-efficient calculation

$$\gamma(X_{0j}, X_{ij}) = \frac{\Delta_{min} + \xi\Delta_{max}}{\Delta_{ij} + \xi\Delta_{max}}$$

Where $\mathbf{\Delta_{ij}= |x_{0j} - X_{ij}|}$ = Absolute value of the difference of $\mathbf{x_{0j}}$

and $\mathbf{X_{ij}}$, and ξ= Distinguishing coefficient varies from 0 to1.

Here we are taking ξ as 0.5.

- Average values for the grey relational co-efficient are calculated using the formulae

$$\boldsymbol{\Gamma = \frac{1}{n}\sum_{k=1}^{n} \gamma(X_i(k), X_j(k))} \quad k{=}number\ of\ test$$

- Mean Grey Relational Grade is calculated using

$$\boldsymbol{\Gamma_m = \frac{1}{n}\sum_{k=1}^{n} \Gamma(k)}$$

- S/N ratio for smaller the better characteristic is calculated by using

$$\frac{S}{N} ratio = -10 log[\frac{1}{n}\sum_{k=1}^{n} X^2{}_{ijk}]$$

- Graphs are to be plotted using the software MINITAB 16, and the optimal settings for the machining process is to be found out.

- Ranking of parameters is to be carried out.

Factorial Design

Full factorial deign-

No. of factors – 2

No. of levels of each factor – 3

No. of blocks – 1

No. of replication -1

No of runs – 9

Table No. 2, Randomized block design

RUN ORDER	BLOCK	A	B	FEED RATE	SPINDLE SPEED	STANDARD ORDER
1	1	2	3	10	2000	6
2	1	2	2	10	1500	5
3	1	1	3	5	2000	3
4	1	3	1	15	1000	7
5	1	2	1	10	1000	4
6	1	1	1	5	1000	1
7	1	3	2	15	1500	8
8	1	1	2	5	1500	2
9	1	3	3	15	2000	9

Table No. 3, Output Response Table

RUN ORDER	TORQUE	THRUST	LOCAL CIRCULARITY ERROR	MACHINING TIME
1	0.1	3.7	0.03	23.52
2	0.1	3.7	0.05	28.88
3	0.1	3.7	0.01	32.48
4	0.1	4	0.01	16.47
5	0.1	3.7	0.01	18.89
6	0.1	3.33	0.01	34.00
7	0.1	3.33	0	20
8	0.1	4	0.02	32.88
9	0.1	3.7	0.02	12.78

NORMALIZATION

For smaller the better characteristics

$$N_{ij} = \frac{(X_{ij})_{max} - X_{ij}}{(X_{ij})_{max} - (X_{ij})_{min}}$$

Table No. 4, Grey Relational Table

RUN ORDER	TORQUE	THRUST	LOCAL CIRCULARITY ERROR	MACHINING TIME
IDEAL SEQUENCE	1	1	1	1
1	0	0.4477	0.4	0.4939
2	0	0.4477	0	0.2413
3	0	0.4477	0.8	0.0716
4	0	0	0.8	0.8261
5	0	0.4477	0.8	0.7120
6	0	1	0.8	0
7	0	1	1	0.6598
8	0	0	0.6	0.0528
9	0	0.4477	0.6	1

CALCULATION OF Δ_{ij}

Using $\Delta_{ij} = |x_{0j} - X_{ij}|$

Table No. 5, For the value of Δ_{ij}

RUN ORDER	TORQUE	THRUST	LOCAL	MACHINING TIME
IDEAL SEQUENCE	1	1	1	1
1	1	0.5523	0.6	0.5561
2	1	0.5523	1	0.7587
3	1	0.5523	0.2	0.9284
4	1	1	0.2	0.1739
5	1	0.5523	0.2	0.2880
6	1	0	0.2	1
7	1	0	0	0.3402
8	1	1	0.4	0.9472
9	1	0.5523	0.4	0

CALCULATION OF GREY RELATIONAL CO-EFFICIENT

Formula used is $\gamma(X_{0j}, X_{ij}) = \frac{\Delta_{min}+\xi\Delta_{max}}{\Delta_{ij}+\xi\Delta_{max}}$Where ξ=0.5

Table No. 6, Grey Relational Co-efficient values

RUN ORDER	TORQUE	THRUST	LOCAL CIRCULARITY ERROR	MACHINING TIME
IDEAL SEQUENCE	1	1	1	1
1	0.3333	0.4751	0.4545	0.4734
2	0.3333	0.4751	0.3333	0.3972
3	0.3333	0.4751	0.7143	0.3500
4	0.3333	0.3333	0.7143	0.7419
5	0.3333	0.4751	0.7143	0.6345
6	0.3333	1	0.7143	0.3333
7	0.3333	1	1	0.5951
8	0.3333	0.3333	0.5556	0.3455
9	0.3333	0.4751	0.5556	1

CALCULATION OF GREY RELATIONAL GRADE

Formula used is $\boldsymbol{\Gamma} = \frac{\boldsymbol{1}}{\boldsymbol{n}} \sum_{\boldsymbol{k=1}}^{\boldsymbol{n}} \boldsymbol{\gamma}(\boldsymbol{X_i}(\boldsymbol{k}), \boldsymbol{X_j}(\boldsymbol{k}))$

Table No. 7, Grey Relational Grade table

RUN ORDER	STANDARD ORDER	GRADES
1	6	0.4341
2	5	0.3847
3	3	0.4682
4	7	0.5307
5	4	0.5393
6	1	0.5952
7	8	0.7321
8	2	0.3919
9	9	0.5910

Total mean = 0.5186

Table No. 8, DOE grey based relational Taguchi Method

Feed Rate	Speed	Grades	S/N Ratio	Mean	Fit Means	Fits SN	Residual Mean	Residual SN
1	1	0.5952	4.50674	0.5952	0.521589	5.65552	0.073611	-1.14878
1	2	0.3919	8.13649	0.3919	0.469422	6.91201	-0.077522	1.22448
1	3	0.4682	6.59137	0.4682	0.464289	6.66708	0.003911	-0.07570
2	1	0.5393	5.36339	0.5393	0.489189	6.21370	0.050111	-0.85031
2	2	0.3847	8.29756	0.3847	0.437022	7.47020	-0.052322	0.82736
2	3	0.4341	7.24820	0.4341	0.431889	7.22526	0.002211	0.02295
3	1	0.5307	5.50302	0.5307	0.654422	3.50393	-0.123722	1.99908
3	2	0.7321	**2.70859**	**0.7321**	0.602256	4.76043	0.129844	-2.05184
3	3	0.5910	4.56825	0.5910	0.597122	4.51549	-0.006122	0.05276

Table No. 9, S/N Ratio ANOVA Tables

Source	D.O.F	Seq SS	Adj SS	Adj MS	F	P
A	2	12.284	12.284	6.142	1.97	0.253
B	2	2.662	2.662	1.331	0.43	0.679
Residual Error	4	12.442	12.442	3.111		
Total	8	27.388				

Table No. 10, ANOVA Table for means

Source	D.O.F	Seq SS	Adj SS	Adj MS	F	P
A	2	0.045997	0.045997	0.022998	1.88	0.266
B	2	0.006031	0.006031	0.003016	0.25	0.792
Residual Error	4	0.048901	0.048901	0.012225		
Total	8	0.100929				

Table No. 11, Response Table for Signal to Noise Ratios

Smaller is better

Level	Feed Rate	Spindle Speed
1	6.412	5.124
2	6.970	6.381
3	4.260	6.136
Delta	2.710	1.256
Rank	1	2

Table No. 12, Response table for means

Level	Feed Rate	Spindle Speed
1	0.4851	0.5551
2	0.4527	0.5029
3	0.6179	0.4978
Delta	0.1652	0.0573
Rank	1	2

Graphs

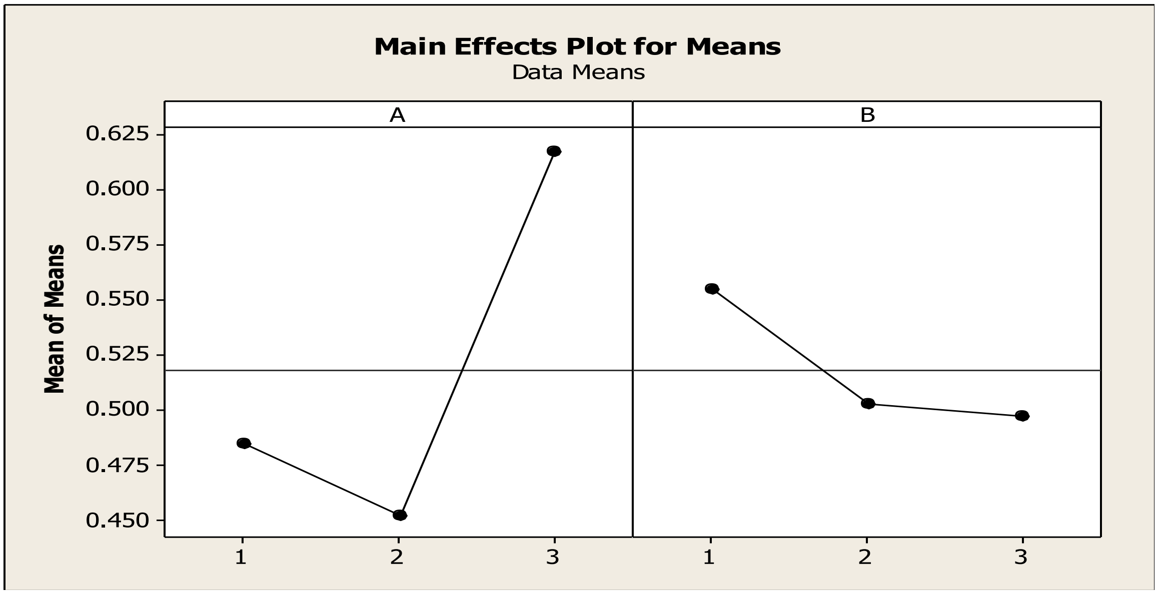

Fig no. 2, Effects Plot for means

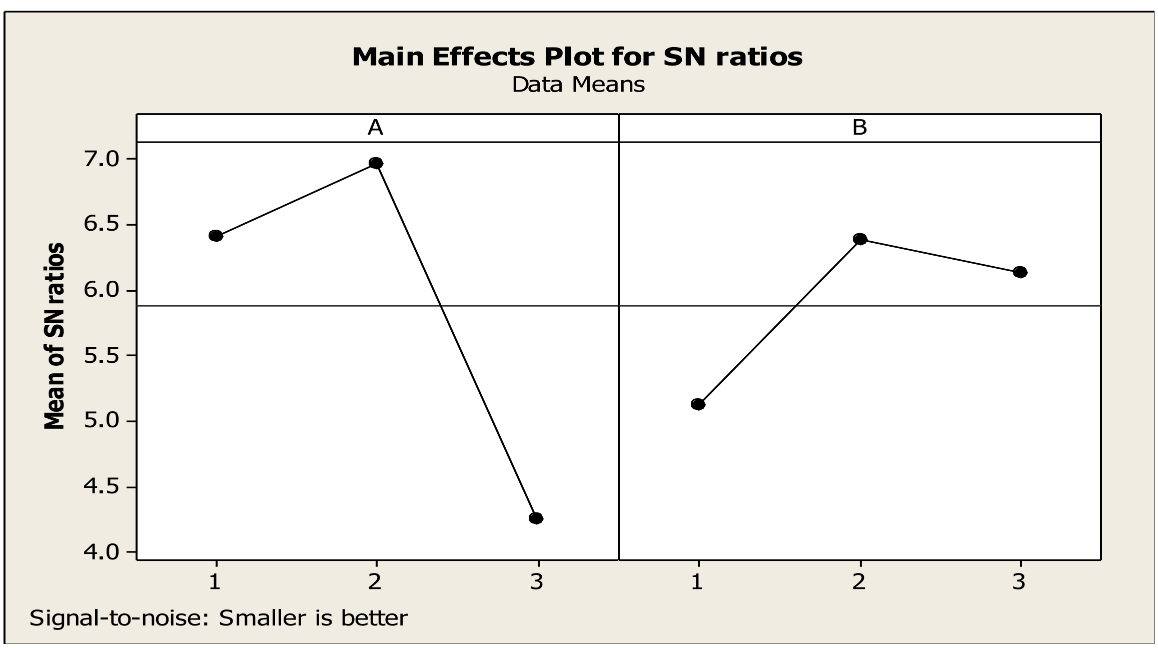

Fig no. 3, Effects Plot for SN ratios

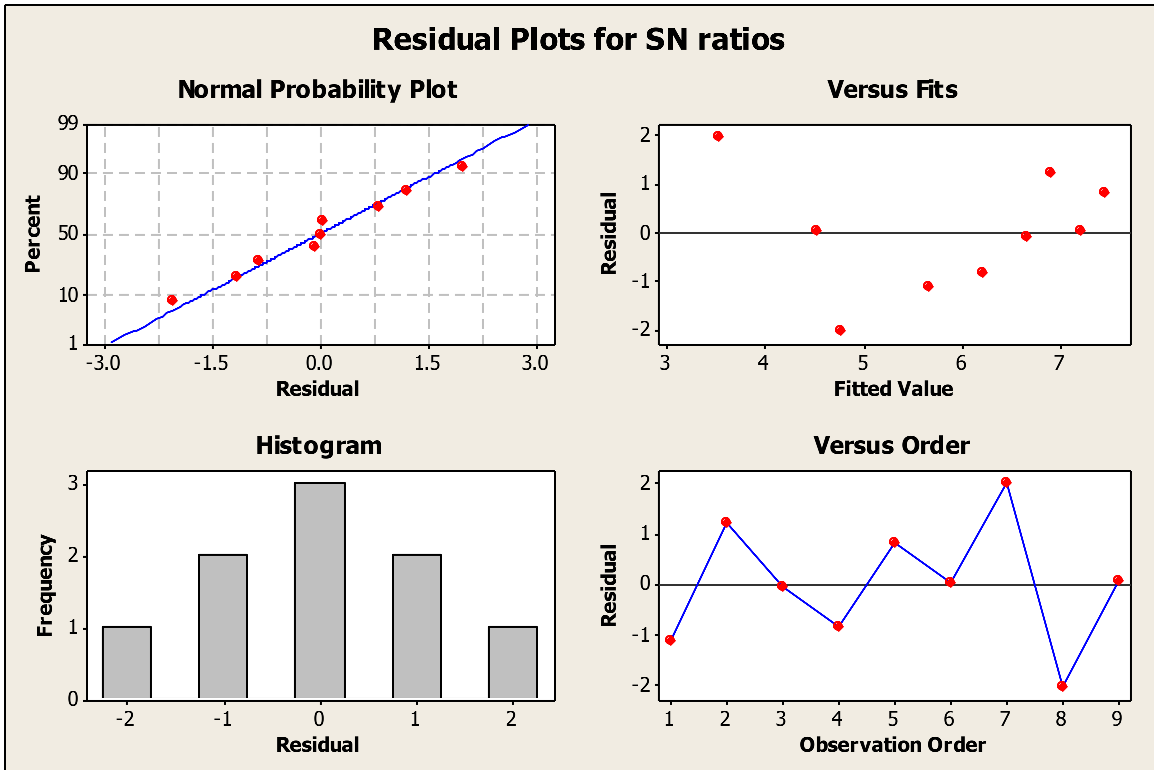

Fig no. 4, Residual plots for SN ratio

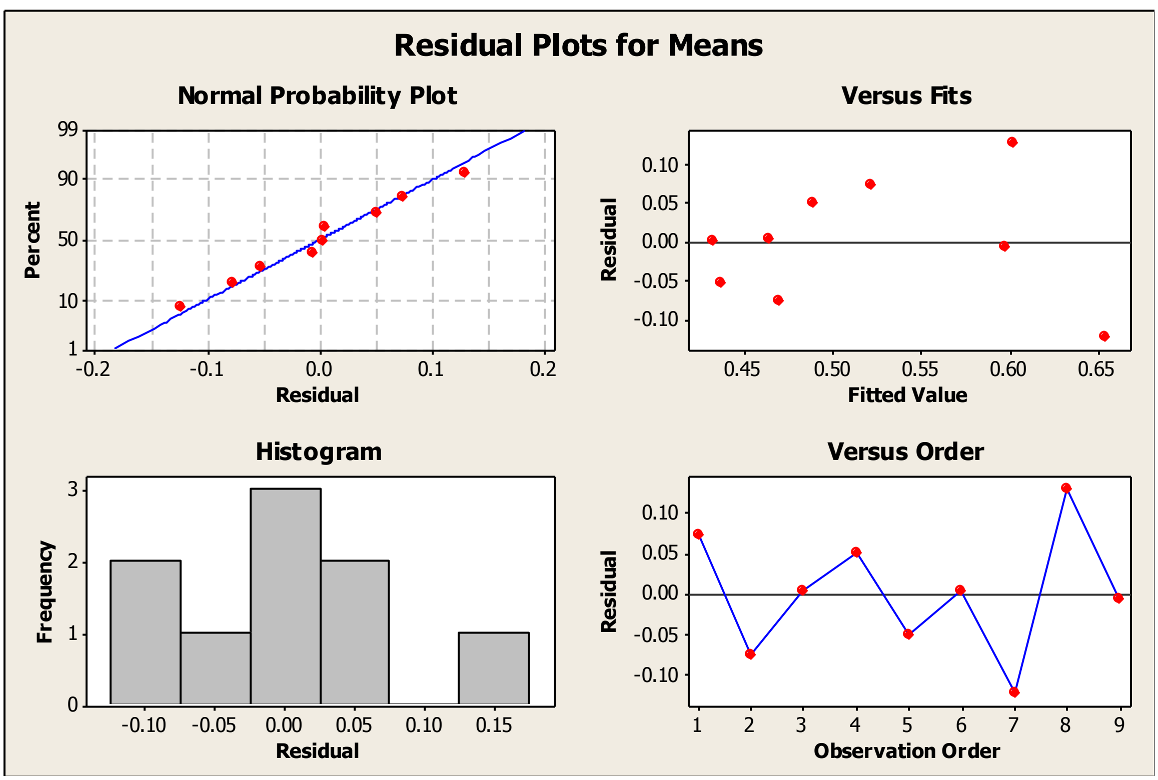

Fig no. 5, Residual plots for Means

Images of holes

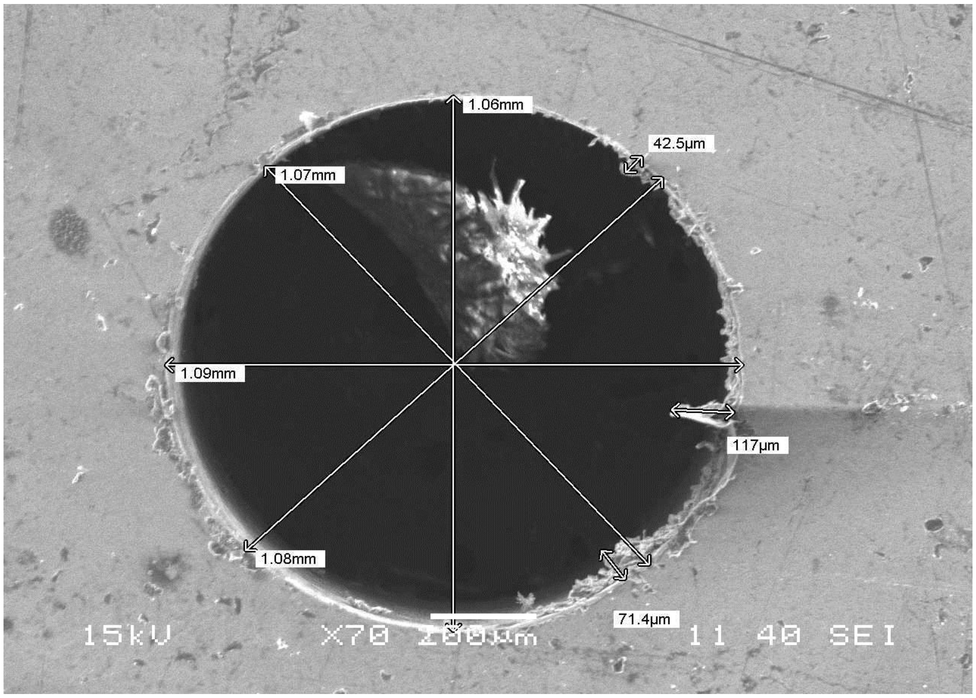

Fig No. 6, Micro hole after run order 1

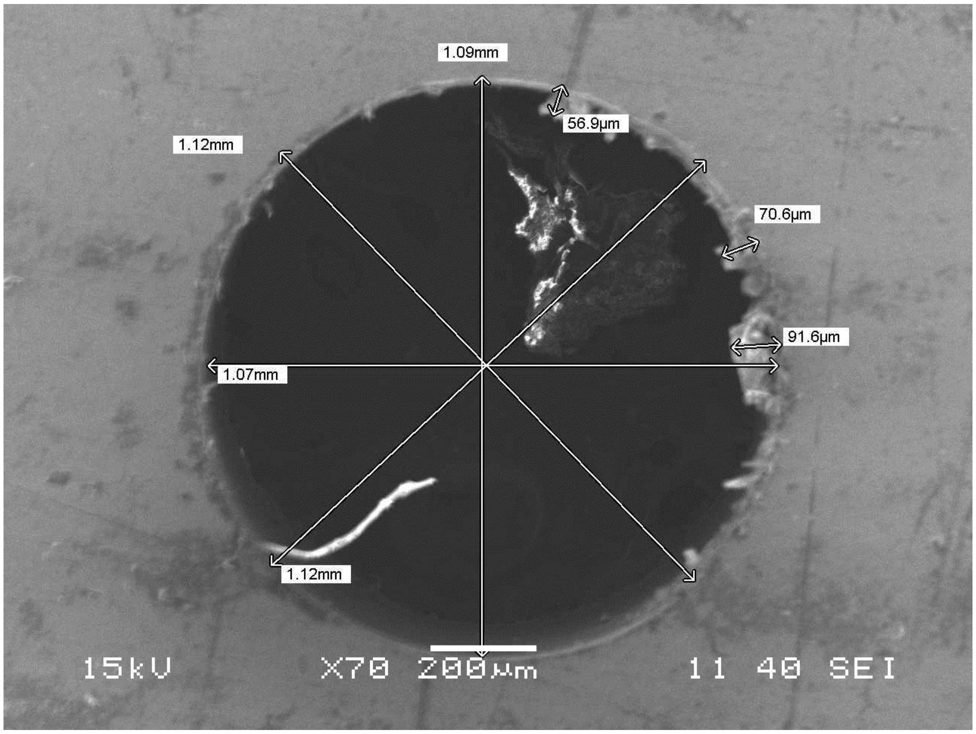

Fig No. 7, Micro hole after run order 2

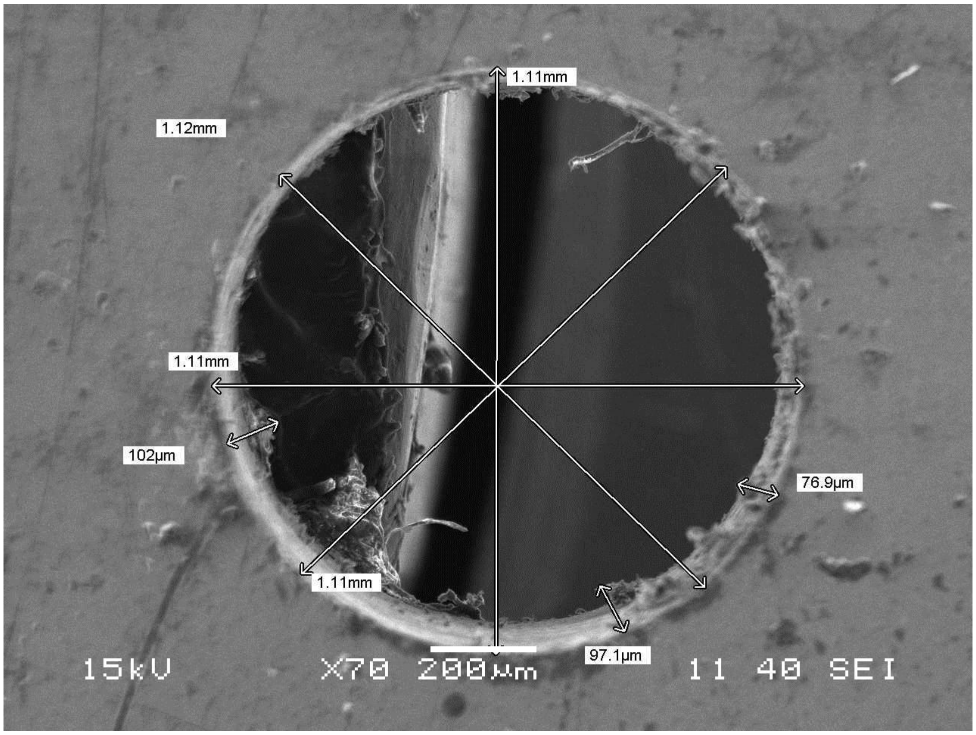

Fig No. 8, Micro hole after run order 3

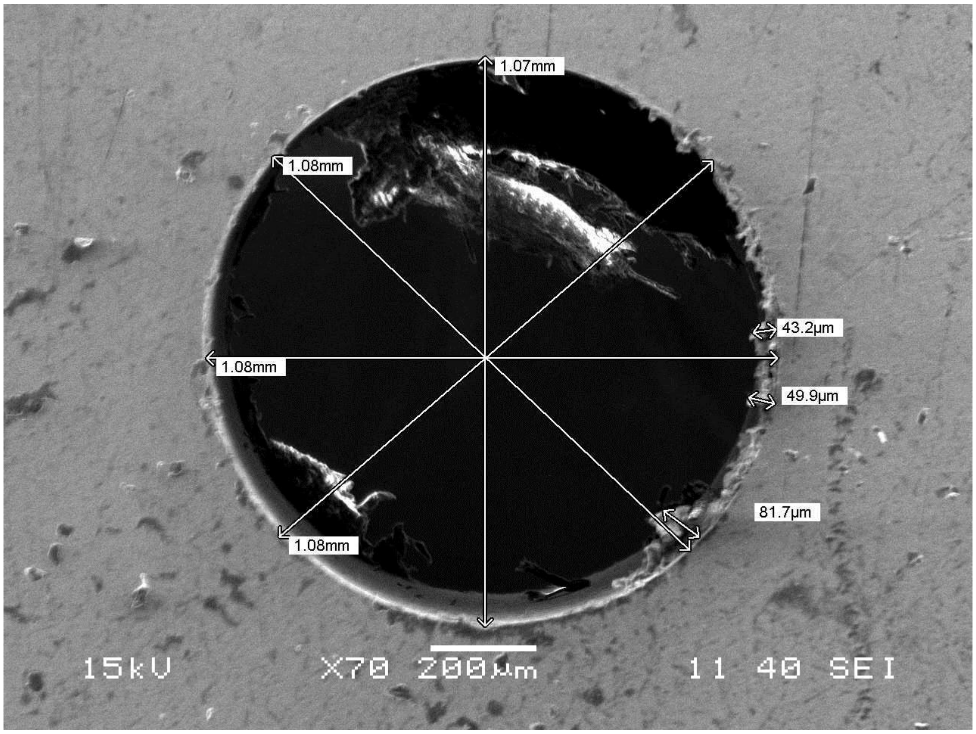

Fig No. 9, Micro hole after run order 4

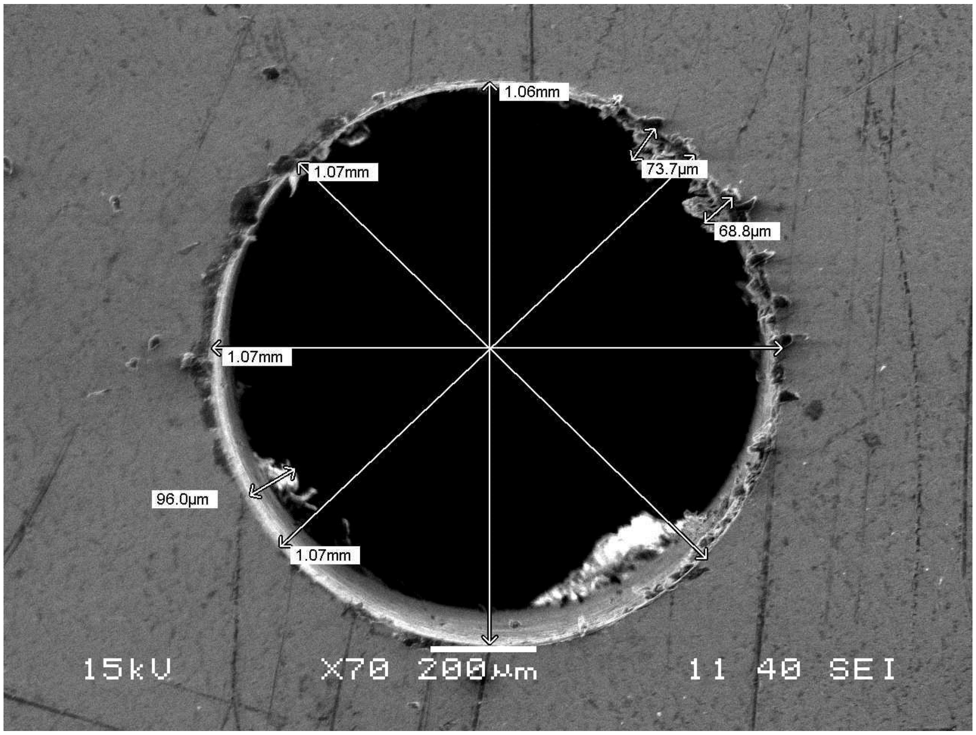

Fig No. 10, Micro hole after run order 5

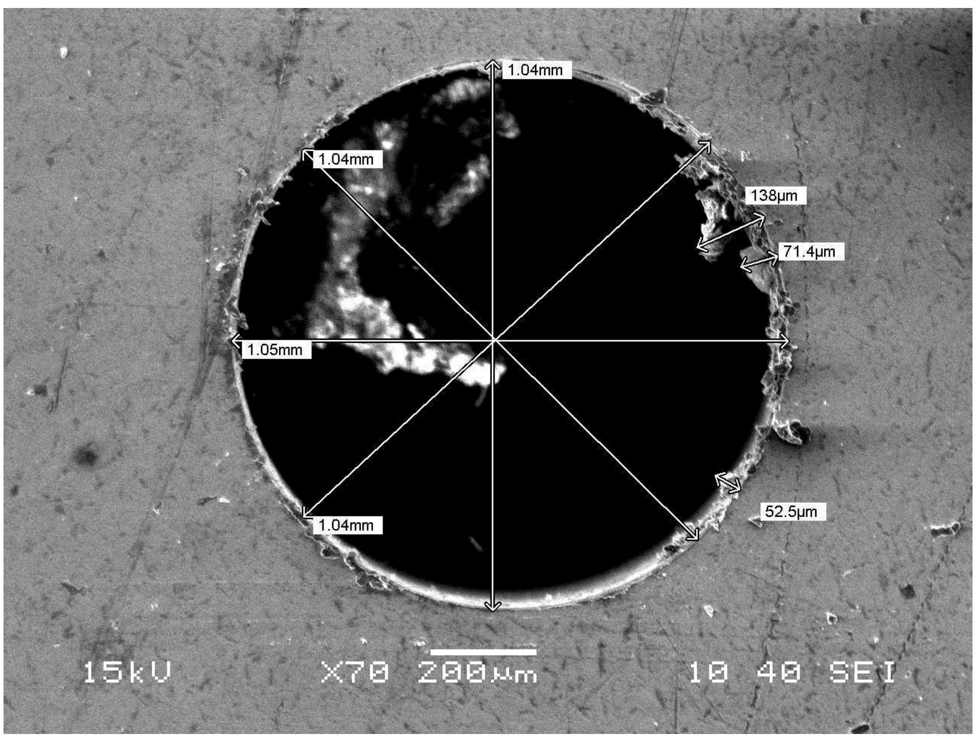

Fig No. 11, Micro hole after run order 6

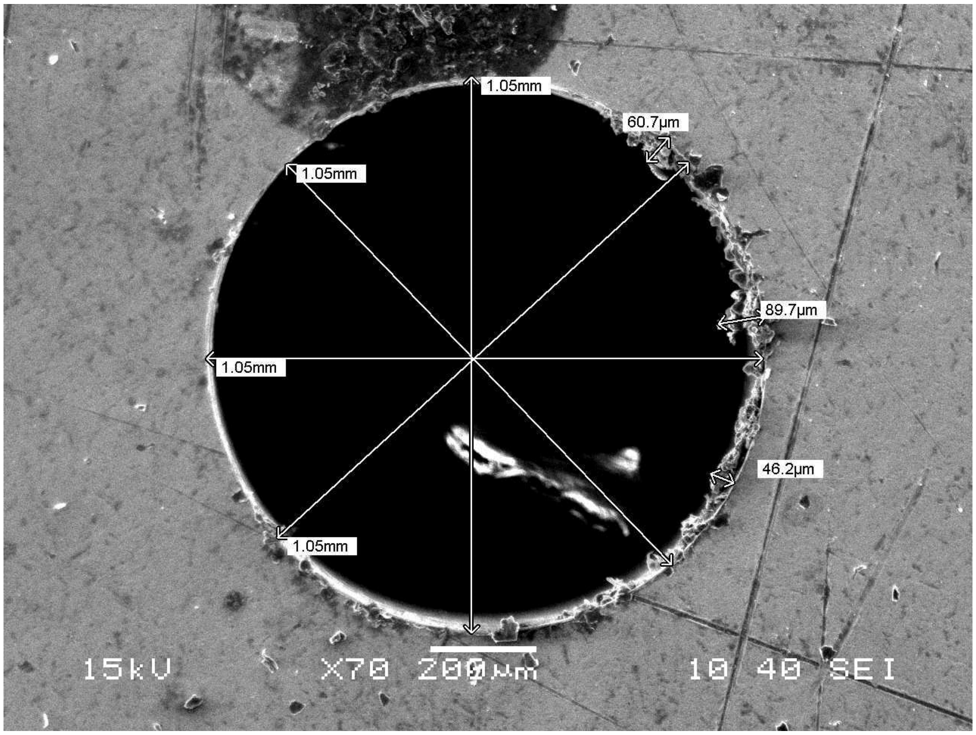

Fig No. 12, Micro hole after run order 7

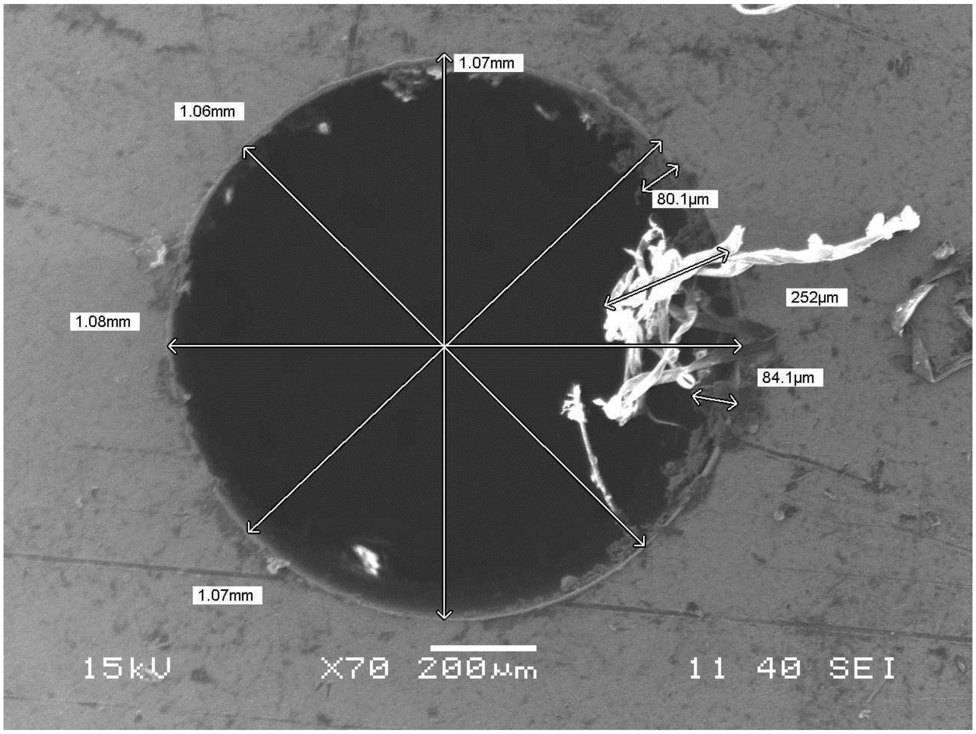

Fig No. 13, Micro hole after run order 8

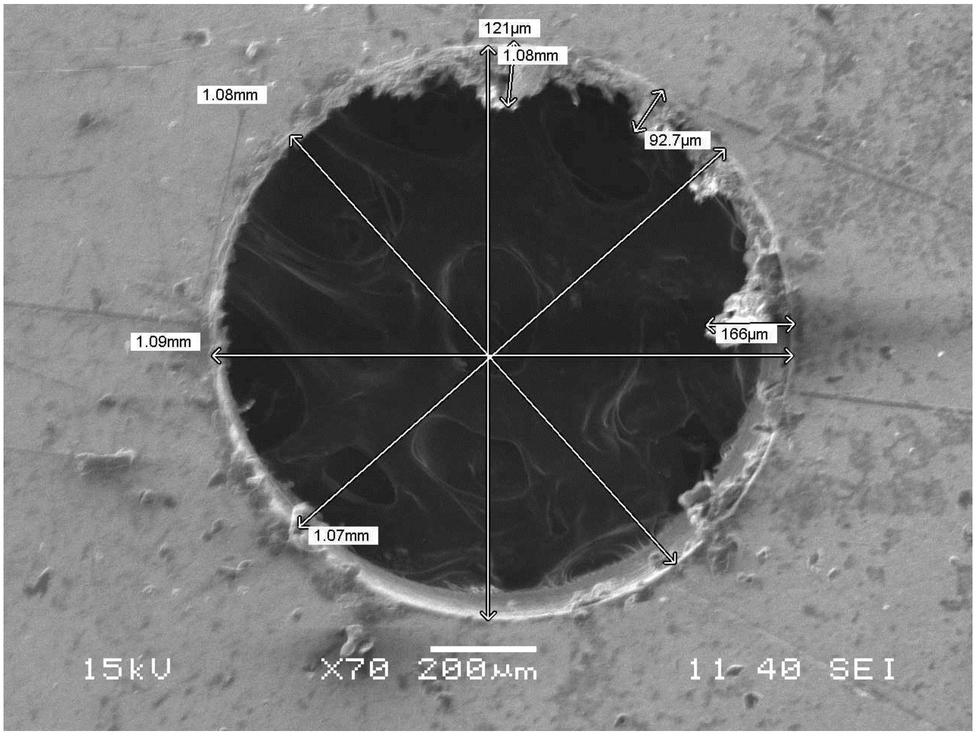

Fig No. 14, Micro hole after run order 9

CHAPTER 6: RESULTS

The results obtained from the experimental procedure are as follows-

1. The minimum value for smaller the better characteristics SN ratio is 2.70859 for 3rd level feed rate(i.e. 15 mm/min) and 2nd level spindle speed(i.e. 1500 rpm).
2. The P value in ANOVA table for means is 0.266 which is less than 0.5, which shows that feed rate is more significant.
3. Feed rate parameter has rank 1 in responsible table which shows more influence.
4. Graph of residual versus fitted value doesn't form any standard platform which indicates absence of error.
5. Normal probability plot of residuals lie near the slope of standardized residual versus percent.
6. The histogram plots are normally distributed.
7. The increased improvement of SN ratio is 2.05184 by 75.75% at optimal condition and for reduced improvement value of mean is 0.129844 by 17.73%.

As a result of this experiment, the multi characteristic drilling process is successfully optimized.

CHAPTER 7: CONCLUSION

The purposed Grey based relational Taguchi method is beneficial for optimization of multi-responded control parameters in micro-drilling process. The main objective of this study was to determine the optimum settings of feed rate and spindle speed so that the thrust force, torque, local circularity error, and machining time can be minimized. The summarized conclusions are given as-

1. The feed rate is the most influential parameter of the operation. As feed rate increases all the output parameters value decrease.
2. Output parameters increases with the increase in spindle speed.
3. The optimum settings for this experiment are at feed rate 15 mm/min and 1500 rpm spindle speed.

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